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### **The effect of variable end of charge battery management on small-cell batteries**

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ABSL Space Products is the world leading supplier of Lithium-ion batteries for space applications and has pioneered the use of small capacity COTS cells within large arrays. This “small-cell approach” has provided many benefits to space application designers through increased flexibility and reliability over more traditional battery designs.

The ABSL 18650HC cell has been used in most ABSL space battery applications to date and has a recommended End Of Charge Voltage (EOCV) of 4.2V per cell. For all space applications using the ABSL 18650HC so far, this EOCV has been used at all stages of battery life from ground checkout to in orbit operations. ABSL and NASA have identified that, by using a lower EOCV for the same equivalent Depth Of Discharge (DOD), battery capacity fade could be reduced.

The intention of this paper is to compare battery performance for systems with fixed and variable EOCV. In particular, the effect of employing the blanket value of 4.2V per cell versus utilizing a lower EOCV at Beginning Of Life (BOL) before gradually increasing it (as the effects of capacity fade drive the End Of Discharge Voltage closer to the acceptable system level minimum) is analyzed.

Data is compared from ABSL in-house and NASA GRC tests that have been run under fixed and variable EOCV conditions. Differences in capacity fade are discussed and projections are made as to potential life extension capability by utilizing a variable EOCV strategy.

# The Effect of Variable End of Charge Battery Management on Small-Cell Batteries



**April 26, 2007**

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- State of Charge (SOC) Analysis Method
- Reduced End of Charge Voltage (REOCV) Results
- Conclusions
- Recommendations



# Testing Background

- Tests designed and commissioned by NASA Glenn Research Center, performed by Crane.
- **Real Time LEO Cycling:** Varied EOCVs, DODs and temperatures from multiple manufactures.
  - 10 ABSL 4s4p modules, employing the ABSL 18650HC cell



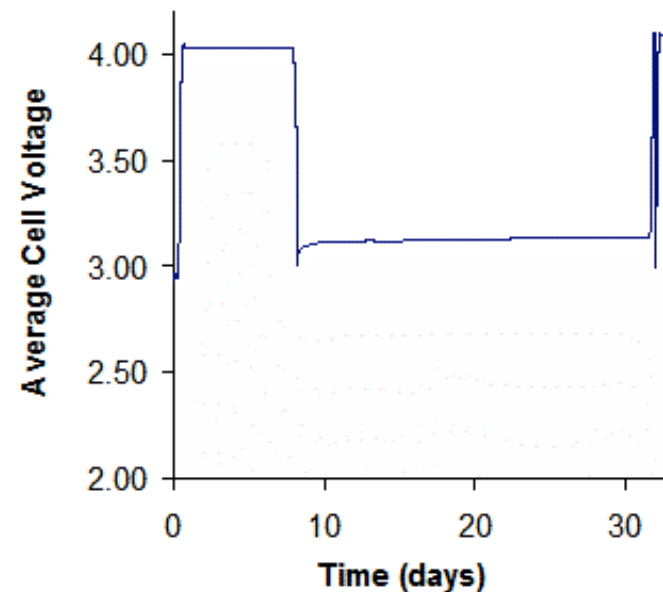
# Testing Background

- **Value to ABSL:** Assess the effects of reduced end of charge voltage (REOCV) on life.
  - It appears that REOCVs could reduce fade based on witnessed storage data.
  - ABSL has extensive life test data at 4.2V EOC, but little at lower EOCVs.
  - Also have extensive flight data from ABSL's 26 launched vehicles



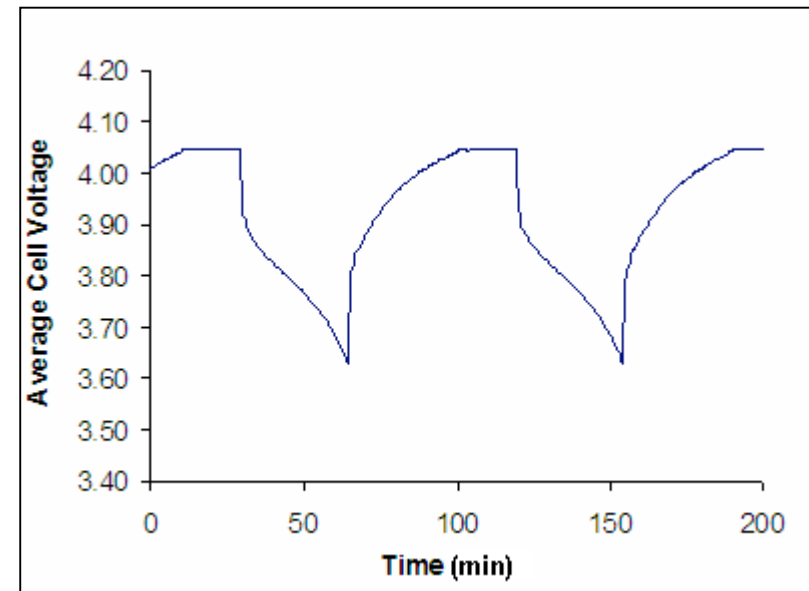
# Testing Background

- **Pre-Cycling Procedures:**
  - Open Circuit Voltage Decay
    - 1 week at 4.1V/cell
  - Capacity Measurement
    - C/2 discharge to 3.0V/cell
    - C/5 charge to 4.1V/cell, taper charge to C/50
    - Approximately 4 cycles per module



# Testing Background

- **Cycling Procedures:**
  - Discharge for 35 minutes, rate based on desired DOD and measured capacity.
  - Charge for 55 minutes, rate selected to replace 110% of removed capacity.





# Testing Background

- **Operational Capacity Measurements**
  - Every 1000 cycles
  - Temperature, rates, and EOCV unchanged from cycling
  - EODV reduced to 3.0V/cell





# Testing Background

## ● Cycling Conditions

Cell EOCV (V)	Temperature (°C)	DOD (%)	Charge Rate (C)	Discharge Rate (C)
4.05	30	20	0.17	0.25
4.05	10	30	0.26	0.37
4.05	20	40	0.35	0.49
4.05	10	40	0.35	0.49
3.95	20	20	0.17	0.25
3.95	30	30	0.26	0.37
3.85	10	20	0.17	0.25
3.85	30	20	0.17	0.25
3.85	20	30	0.26	0.37
3.85	30	40	0.35	0.49

More than 4,000 cycles and  
counting...

The Effects of Variable End of Charge



# SOC Analysis Method

- Need to compare capacity fade between varied EOC and DOD cases, but this is not straightforward...
  - Few operational capacity measurements available with different conditions between cases.
  - Can't directly compare EODV's because of different EOCV's, DOD's, rates, and temperatures.
  - Therefore, a method to calculate total capacity independent of cycling conditions has been derived.

Calculate EMF  
@ EOD, EOC

Calculate  $\Delta$ SOC  
from EOC to EOD

Use change in  
 $\Delta$ SOC over time to  
calculate fade



# SOC Analysis Method

- First, calculate cell resistance @ EOD.

$$\Delta V_1 = -R_{EOD} I_{EOD}$$

$$\Delta V_2 = R_{EOD} I_{BOC}$$

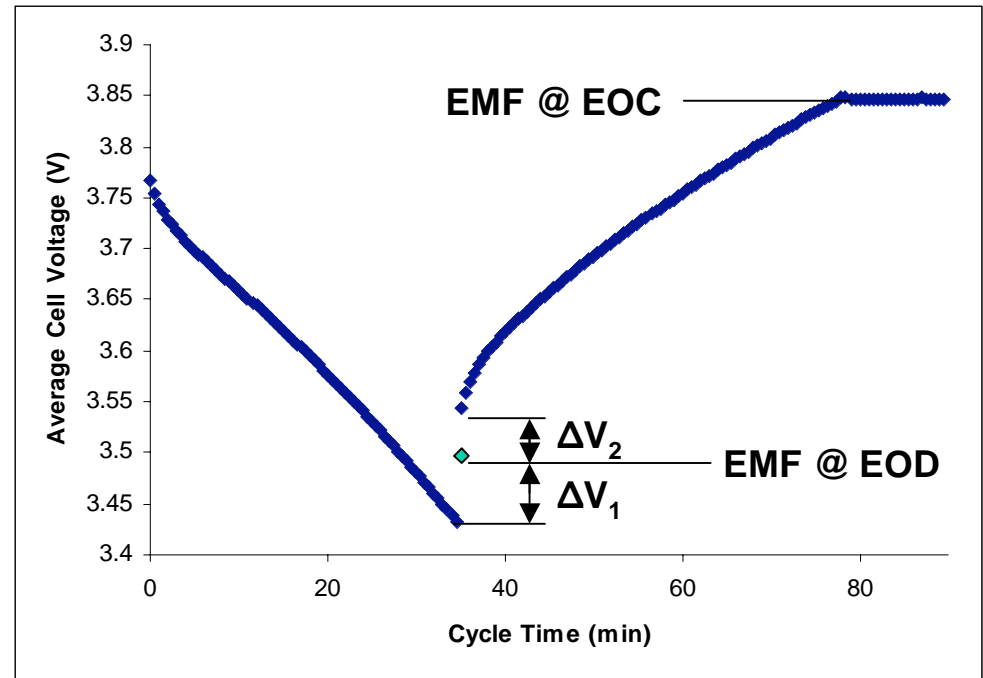
$$R_{EOD} = (\Delta V_1 + \Delta V_2) / (I_{BOC} - I_{EOD})$$

- Next, calculate EMF @ EOD

$$EMF_{EOD} = V_{EOD} - I_{EOD} R_{EOD}$$

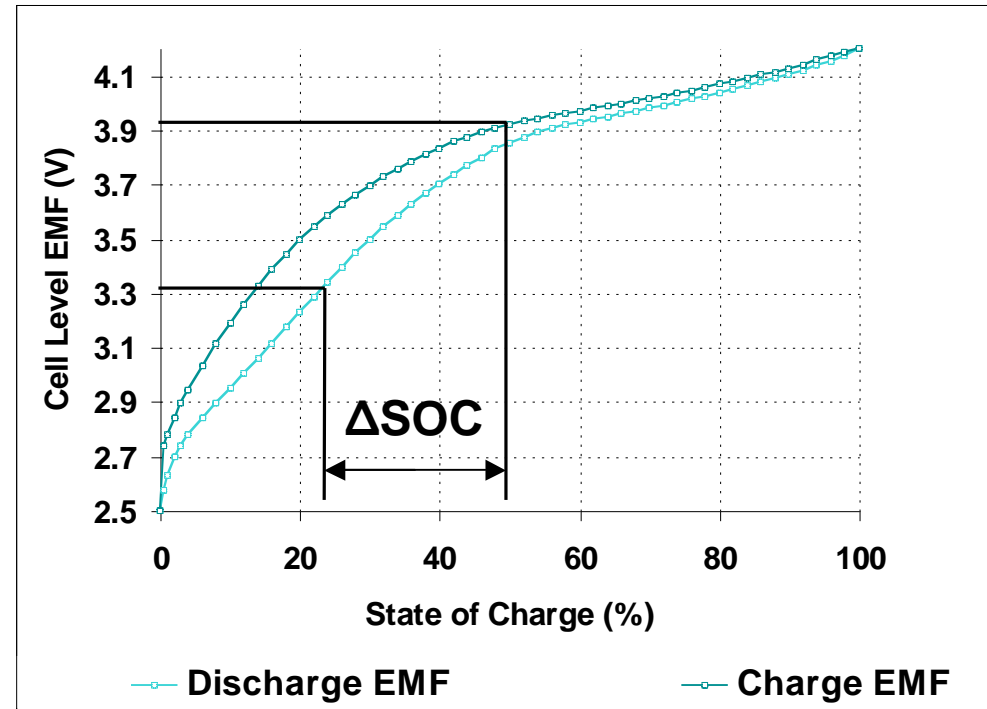
- Then calculate EMF @ EOC assuming negligible difference from terminal voltage.

$$EMF_{EOC} = V_{EOC}$$



# SOC Analysis Method

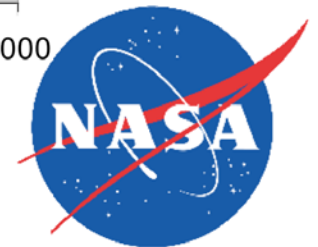
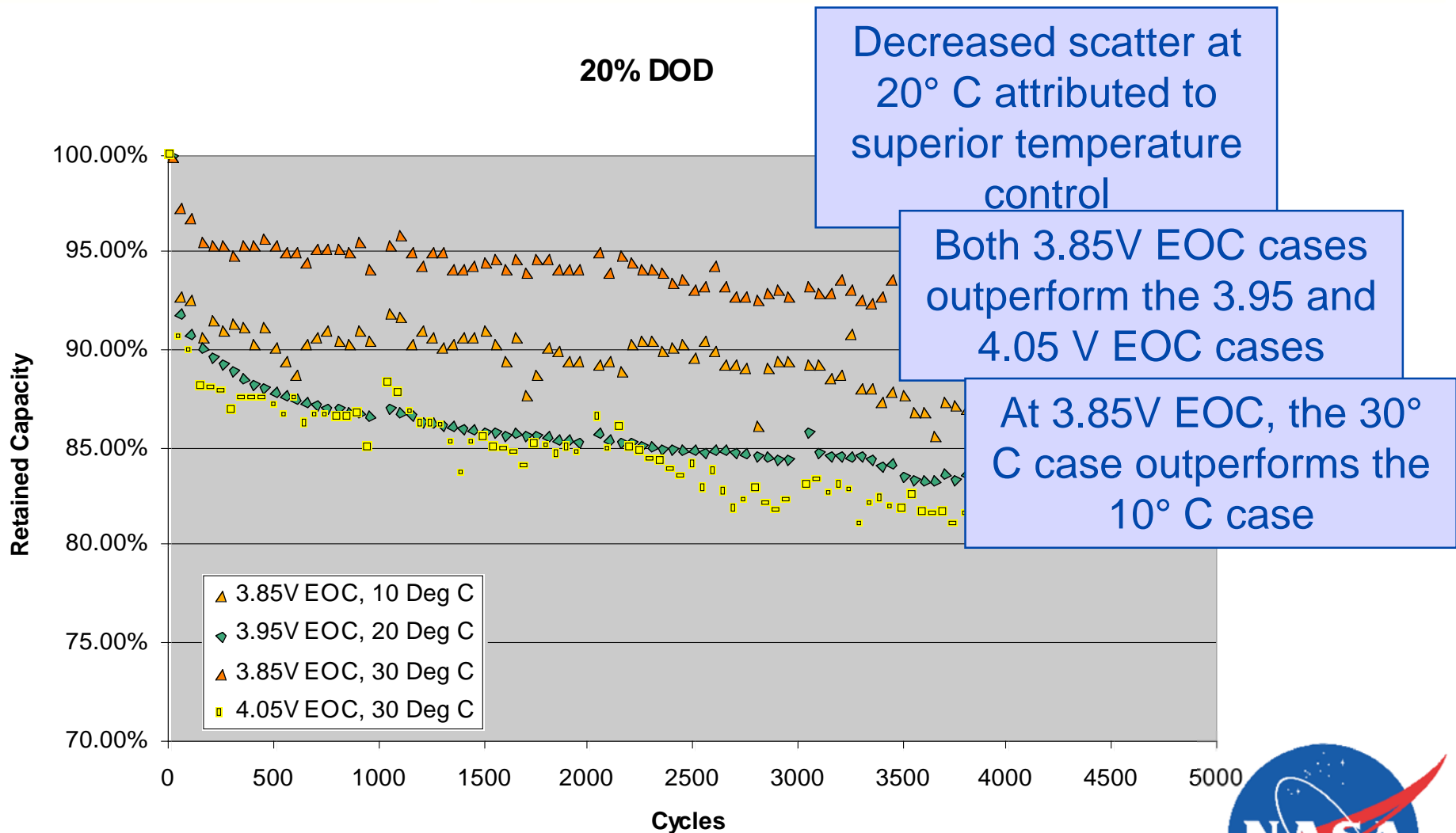
- Calculate change in state of charge ( $\Delta SOC$ ) for each discharge.
- Calculate percent retained capacity by dividing the change in state of charge of the first discharge ( $\Delta SOC(1)$ ) by the  $\Delta SOC(N)$  of any later discharge.
  - EMF vs. SOC plot must be known over life.



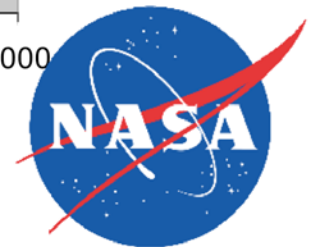
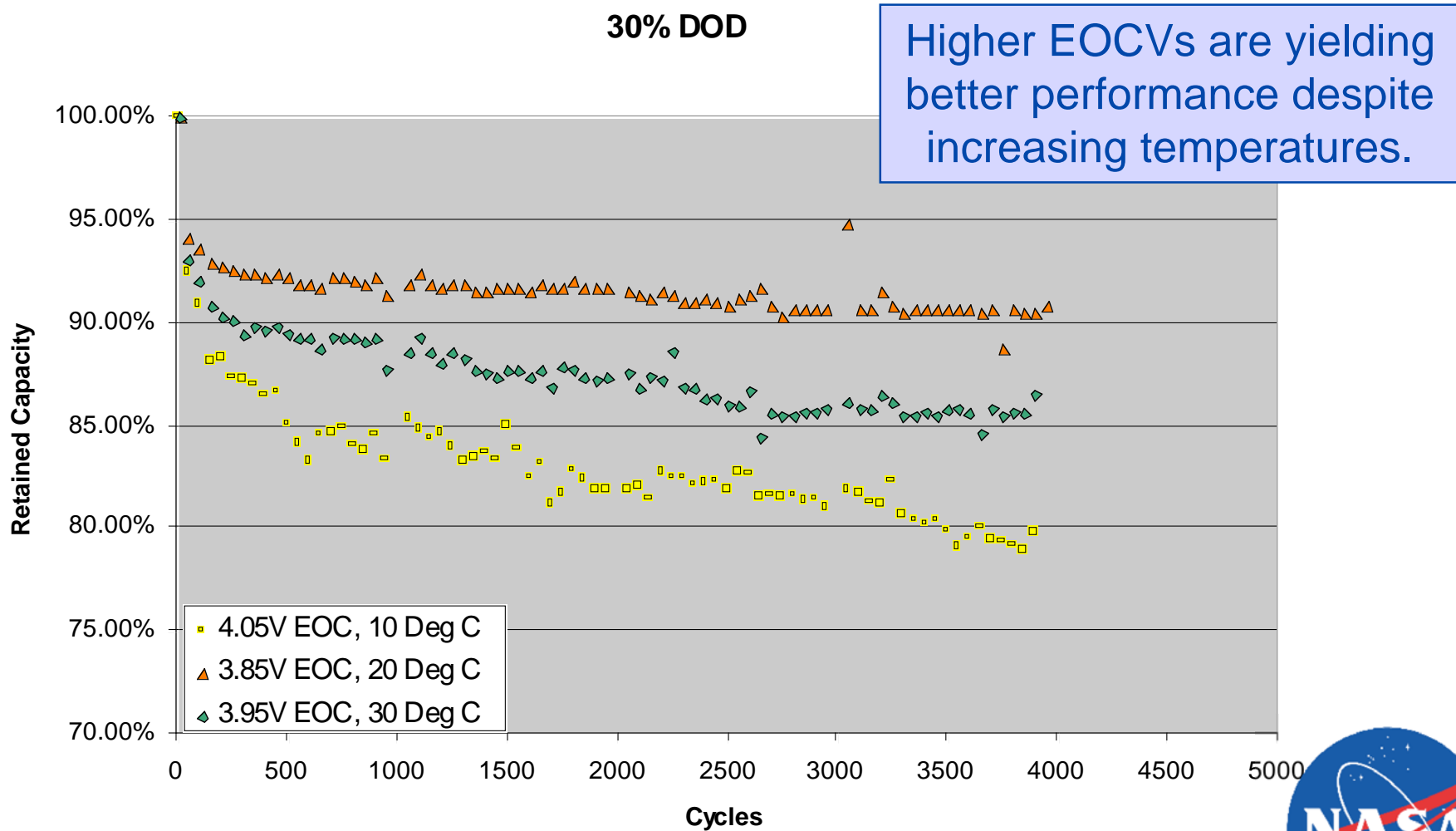
$$\text{Retained Capacity (N)} = 100\% \times \Delta SOC (1) / \Delta SOC (N)$$



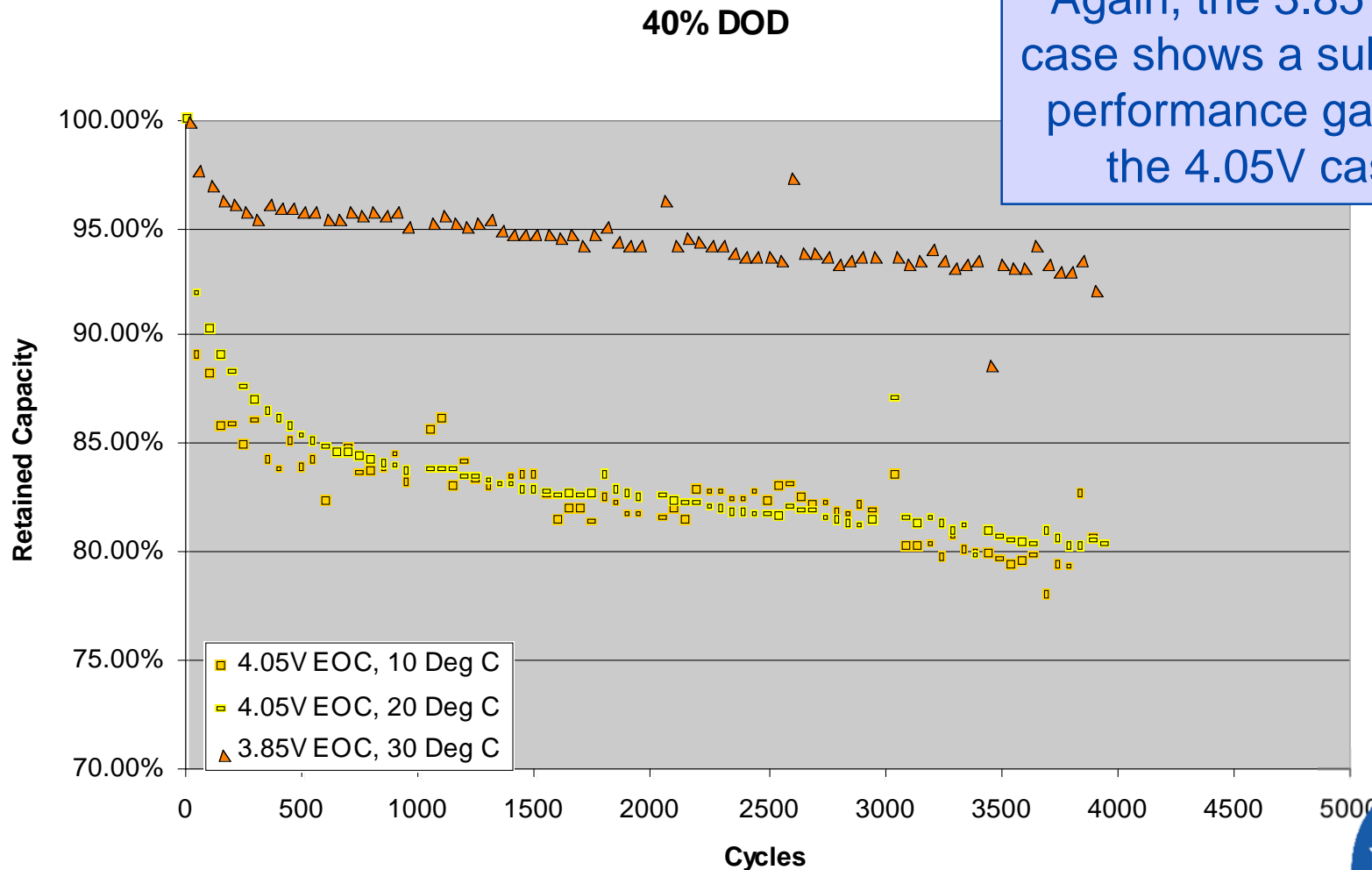
# 20% DOD Performance



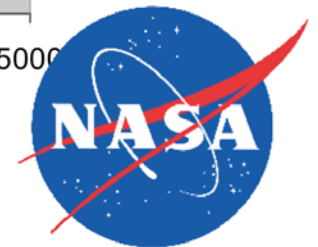
# 30% DOD Performance



# 40% DOD Performance



Again, the 3.85V EOC case shows a substantial performance gain over the 4.05V cases.



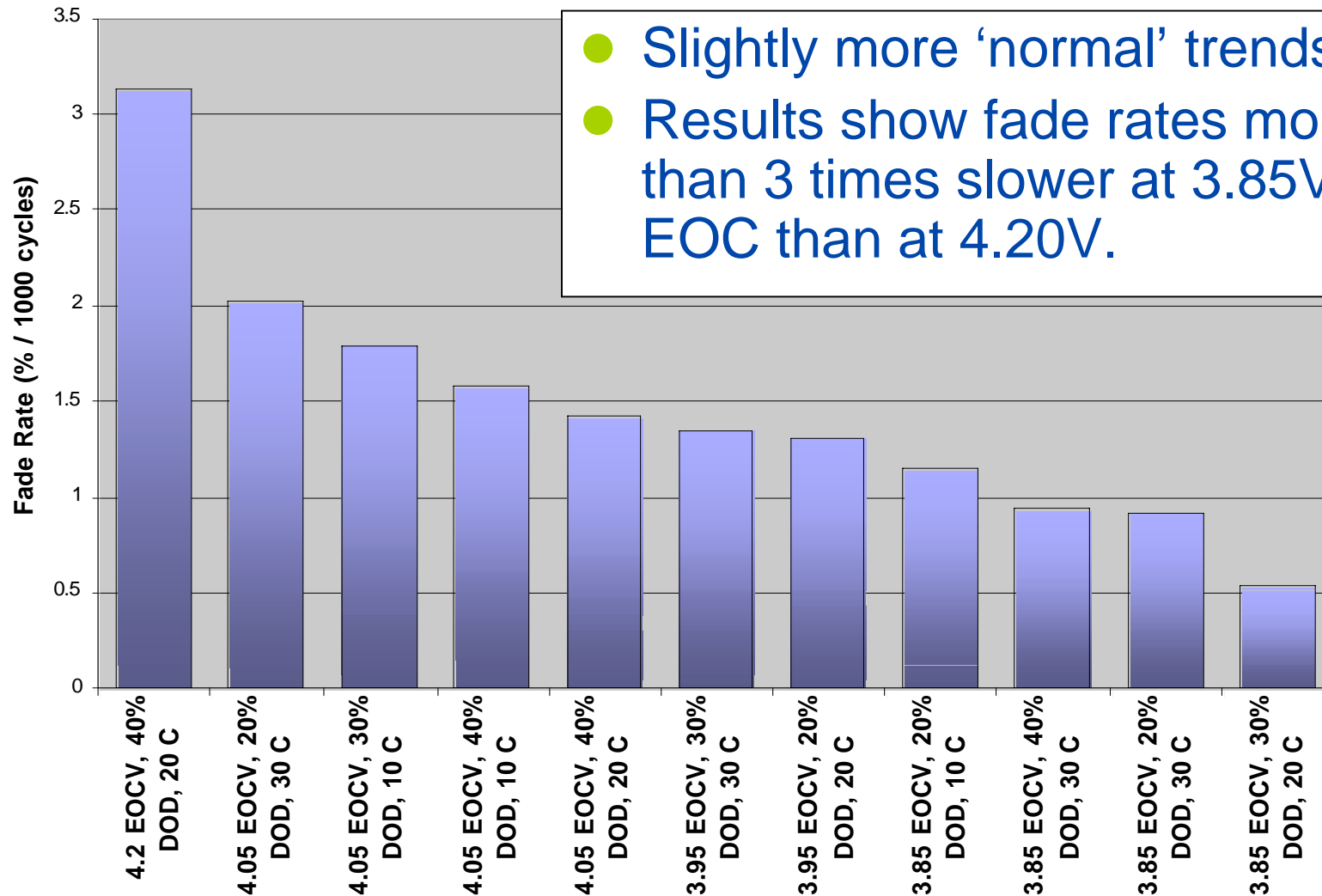


# Results

- Abnormal temperature and DOD dependence: within EOCV groups, some cases show improved capacity retention with higher temperature and DOD.
  - Suspect sensitivity with respect to selecting the reference cycle ( $\Delta\text{SOC}(1)$ ) in the SOC analysis method.
  - Re-reference to an early cycle in the linear region and compare fade rates only.



# Steady State Fade Rates

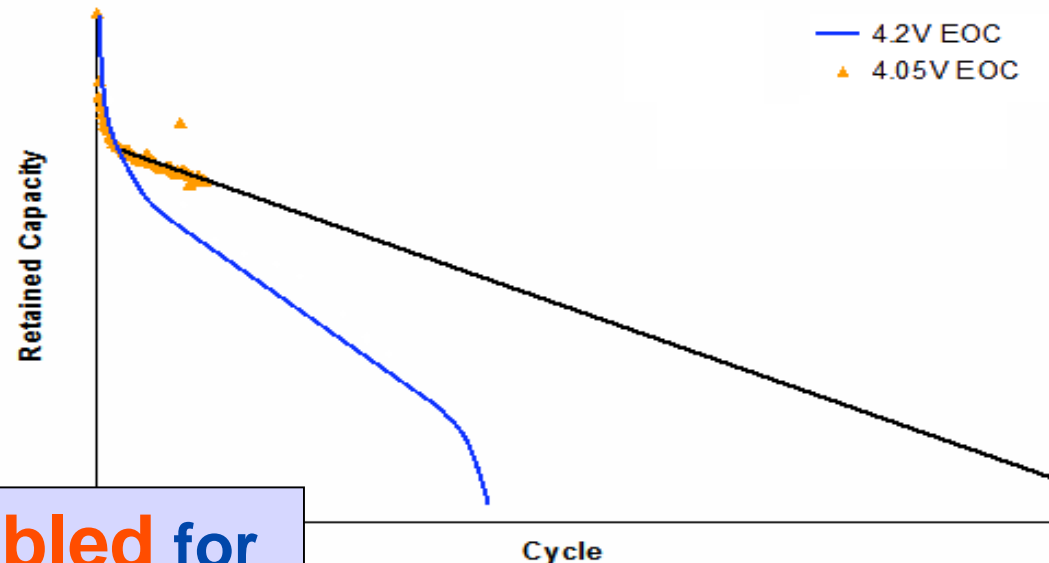


- Slightly more 'normal' trends
- Results show fade rates more than 3 times slower at 3.85V EOC than at 4.20V.



## Case Study

- 4.2V EOCV life test data shows three regions.
- Batteries typically sized to operate to the end of region 2.
- Assuming...
  - End of region 2 is at the same retained capacity
  - Region 2 fade rate stays linear

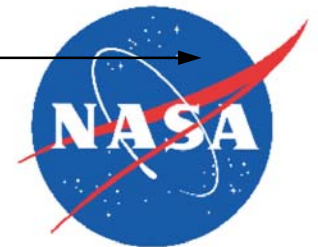
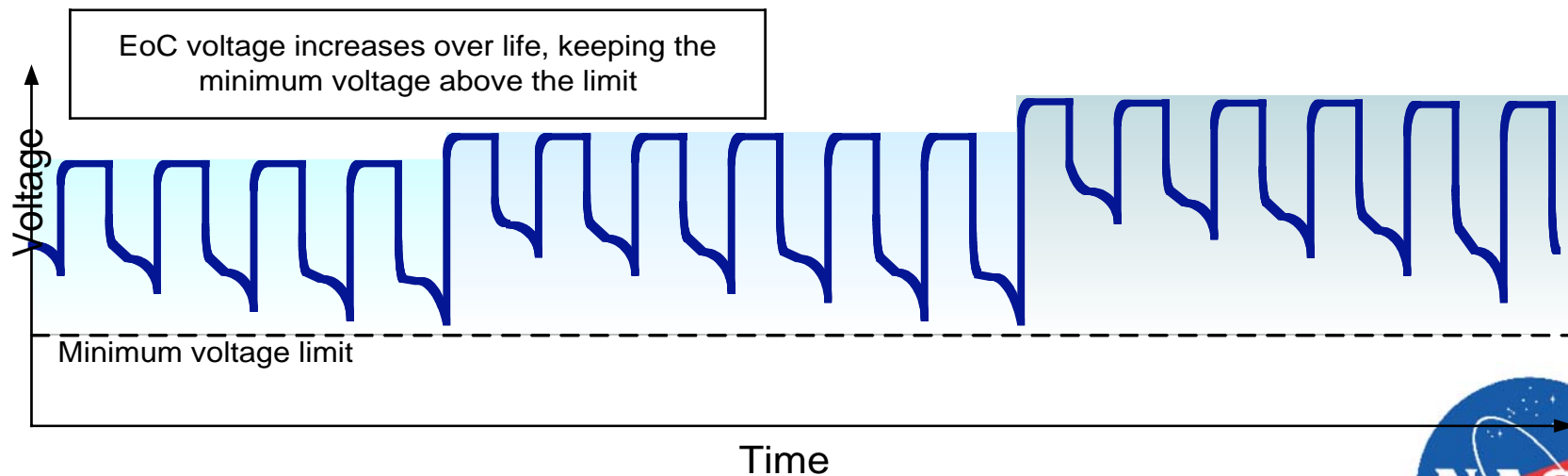


Lifetime could be **doubled** for **40% DOD** missions by reducing EOCV from 4.2V to 4.05V



## Case Study

- Extrapolating the first 4,000 cycles is a stretch, but...
  - Reducing the EOCV below 3.85V should offer an even slower fade rate, and...
  - The user can raise the EOCV each time the EOD cutoff voltage is met.



# Conclusions

- **Operation at reduced end of charge voltages offers a clear benefit in retained capacity in early cycling.**
  - On the order of half the steady-state fade rate
  - More data is needed to identify long term benefits
- **Given the excellent cycle life of the ABSL 18650HC cell at 4.2V EOC, REOCV techniques could support extremely long duration missions or a substantial reduction in battery sizes.**
  - **70,000** cycles and counting at 10% DOD
  - **35,000** cycles and counting at 20% DOD
  - Contact ABSL for further information



# Recommendations

- Commission higher DOD lifetests at reduced EOCVs
  - The 20, 30, and 40% DODs are fairly conservative
  - Higher DODs could be employed to reduce battery mass for the same lifetime, this data could better identify the magnitude of the improvement.
- ABSL will incorporate REOCV life testing as standard practice on its next-generation cells.



# Acknowledgements

